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Nuclear Theory Group

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Research Activities

(I) PHYSICS OF HADRONS AND NUCLEI AT HIGH ENERGIES

a. Effects of friction on the chiral symmetry restoration in high energy heavy-ion collisions
(M. Ishihara and F. Takagi)

Effects of friction on the chiral symmetry restoration in high energy heavy ion collisions was investigated in detail. It was found that the maximum temperature must be high enough (not lower than 230 MeV) and the friction must be strong enough in order that the chiral symmetry restoration lasts for a long time.

b. Effects of friction on the parametric amplification of pion field in the late stage of heavy-ion collisions at high energies
(M. Ishihara and F. Takagi)

We studied the effects of the expansion of the system and the friction on the parametric amplification of mesonic fields in high energy heavy ion collisions using the linear sigma model. It was found that a strong peak may appear around 267 MeV in the pion transverse momentum distribution in cases with weak friction and high maximum temperature.

c. Chiral phase transition at high temperature and density in the QCD-like theory
(O. Kiriyama, M. Maruyama and F. Takagi)

Chiral phase transition at finite temperature T and/or finite chemical potential μ was studied using the QCD-like theory with a variational approach. Modified Cornwall-Jackiw-Tomboulis effective potential was derived for generally nonzero current quark

mass. We then calculated the effective potential at finite T and/or μ in the chiral limit to investigate the phase structure. We found a tricritical point at $T = 107$MeV and $\mu = 210$MeV. It separates the second order phase transition at higher T and lower μ and the first order transition at higher μ and lower T.

d. Effects of finite quark mass on chiral phase transition of QCD in the improved ladder approximation
(O. Kiriyama, M. Maruyama and F. Takagi)

Effects of finite quark mass on the chiral phase transition of QCD was investigated in the improved ladder approximation. We used the Schwinger-Dyson equation to modify the Cornwall-Jackiw-Tomboulis effective potential. The relevant critical exponents and the masses of the scalar and the pseudoscalar mesons at finite temperature were calculated.

e. QCD phase structure in diquark-meson model
(K. Sato, O. Kiriyama, M. Maruyama and F. Takagi)

An effective action which takes into account the diquark and the meson (quark-antiquark) correlations was constructed in the abelianized QCD by using auxiliary fields. The effective potential was derived in order to investigate the phase structure of QCD.

f. Meson-baryon coupling and magnetic moment of the octet baryons in the quark-diquark picture
(M. Iwasaki and F. Takagi)

The quark-diquark picture of the $J^P = \frac{1}{2}^+$ octet baryons was used to study the SU(3) structure of the coupling constants between the octet baryons and the $J^P = 0^-$ octet mesons. The same picture was also used to calculate the magnetic moment of the octet baryons. We found a nonet-like symmetry with $F/D = -1$ in the meson-baryon coupling scheme.

g. Supercooling and reheating in hadronization of quark-gluon plasma
(F. Takagi)

First order phase transition from quark-gluon plasma into hadron gas via nucleation was studied. We found the possibility that the critical radius of the hadron droplet may be a constant independent of the temperature by considering temperature fluctuation and the energy conservation in the domain of nucleation. This leads to a new scenario which is quite different from the standard Csernai-Kapusta scenario.

h. Spontaneous Pair Creation and Time Evolution of Vacuum in a Uniform Electric Field
(Y. Nakazawa and M. Maruyama)

The time evolution of the vacuum state in a uniform electric field is studied. We solve the Heisenberg Equation of motion of the Dirac fermion in an external field. Evolution of the creation and annihilation operators are expressed as the time-dependent Bogolioubov transformation. We find that the survival probability of the vacuum state per unit volume obeys the Gaussian decay law instead of the exponential decay law at short time.

(II) LOW ENERGY HEAVY-ION COLLISIONS AND MACROSCOPIC QUANTUM TUNNELING

a. Coulomb interaction between a spherical and a deformed nuclei
(N. Takigawa, Tamanna Rumin and N. Ihara)

We derived analytic expressions of the Coulomb interaction between a spherical and a deformed nuclei which are valid for all separation distance. We then demonstrated their significant deviations from commonly used formulae in the region inside the Coulomb radius, and showed that they remove various shortcomings of the conventional formulae.

b. Heavy-ion fusion reactions with proton- and neutron-rich unstable nuclei
(N. Takigawa and Tamanna Rumin)

We studied the effects of difference of the charge and matter deformation parameters in heavy-ion fusion reactions using the fusion of ^{19,37}Na isotopes with ^{208}Pb.

c. Landau-Zener Transition In the Presence of Potential Barriers and Pockets
(N. Takigawa, T. Tazawa, M. Ueda and Y. Abe)

We derived analytic formulae for the S-matrix for a two level crossing problem in the presence of potential barriers and pockets by using a three turning point semiclassical theory for a scattering problem and a matrix formalism for the non-adiabatic transition. Our semiclassical S-matrices satisfy the unitarity condition and the elastic and inelasitic S-matrix elements reduce to improved Landau-Zener-Stückelberg formulae at high energies where the existence of the potential barriers can be ignored. We discussed qualitative behaviors of the semiclassical S-matrix elements in the weak and strong coupling limits, i.e. in the limits where the one-way Landau-Zener transition probability $p \to 1$ and $p \to 0$, respectively. Also we gave detailed discussions on the interplay between the Landau-Zener transtion and a potential resonance.

(III) α DECAY

a. Reexamination of the α Decay theory
(N. Takigawa, Y. Nozawa and K. Hagino)

We examined the R-matrix theory for the α decay and found that a care should be taken in the preexponential factor in applying the WKB formula to the barrier penetrability.

(IV) SUPER HEAVY ELEMENTS

a. The structure of superheavy elements
(N. Takigawa and Jie Meng)

We performed a systematic study of the structure of superheavy elements claimed to have been discovered in the recent ^{208}Pb(^{86}Kr,n) reaction at Berkeley using the Relativistic Mean Field (RMF) approach. We showed that various usually employed RMF forces, which give fair description of normal stable nuclei, give different predictions for superheavy elements. Among the effective forces we tested, TM1 seems to be the good

candidate to describe superheavy elements. The binding energies of the $^{293}118$ nucleus and its $\alpha-$decay daughter nuclei obtained using TM1 agree with those of FRDM within 2 MeV. Similar conclusion that TM1 is the good interaction has been drawn also from the calculated binding energies for Pb isotopes with the Relativistic Continuum Hartree Bogoliubov (RCHB) theory. Using the pairing gaps obtained from the RCHB for protons and filling approximation for neutrons to simplify the blocking effect, we carried out the RMF calculations with deformation for the structure of superheavy elements. We thus discussed the binding energy, shape, single particle levels, and the Q values of the $\alpha-$decay Q_α and showed that the pairing correlation, blocking effect and deformation are essential to properly understand the structure of superheavy elements. We also calculated the Q_α values for the ground state to ground state transitions and for those respecting the angular momentum selection rule, and compared them with data.

(V) SCREENING EFFECTS BY BOUND ELECTORONS ON NUCLEAR REACTIONS AT EXTREMELY LOW ENERGIES

(N. Takigawa and S. Kimura)

We studied the screening effects by the bound electron in the D+ ^{3}He and ^{3}He$^+$+d reactions at astrophysically low energies in laboratory experiments. To this end, we developed a semiclassical mean field theory which enables to describe both classical and tunneling regions. We thus found that the screening potential is not constant in the tunneling region as has been assumed in previous studies. We have also shown that a strong non-adiabatic transition of the electron is induced in the tunneling region in the D+ ^{3}He reaction, where the electron occupies the second excited state of the unified system at the beginning of the reaction. We have then suggested that both of these novel effects lead to a larger screening effect than hitherto estimated and might lead to even a lager screening energy than the simple minded adiabatic limit, where the screening energy is identified with the difference of the binding energies of the electron in the target and in the unified atoms. We also remarked that this simple estimate is valid only when the tunneling region is smaller than the region, where the electron in the unified atom is distributed.

(VI) METALCLUSTER PHYSICS

a. Phase transition of Na clusters

(K. Yoshizaki, A. Ono and N. Takigawa)

We developed a comuter code to study the phase transition of Na clusters based on the first principle molecular dynamics.

(VII) MICROSCOPIC STUDY OF INTERMEDIATE ENERGY HEAVY ION REACTIONS

a. Effects of the Stiffness of Nuclear Matter in Fragmentation Reactions

(A. Ono)

A surface correction term is introduced to a variant of the Gogny force with a stiff incompressibility ($K = 373$ MeV) in order to have a reasonable description of finite nuclei. The antisymmetrized molecular dynamics (AMD) calculations are performed with this stiff

Gogny force as well as with the usual Gogny force ($K = 228$ MeV), in order to discuss the effect of the equation of state (EOS). In $^{40}Ca + ^{40}Ca$ at 35 MeV/u where the reaction is basically binary, larger dissipation is obtained for stiffer EOS. α particles are produced abundantly from the projectile and target components only when the EOS is soft. On the other hand, in more violent collisions (Au + Au at 150 MeV/u), similar effect is found for the degree of the transparency, while the charge distribution of fragments is insensitive to the stiffness.

b. Isospin Effects in $^{58}Ni + ^{58}Ni$ and $^{58}Fe + ^{58}Fe$ Collisions
(A. Ono)

The isospin dependence of the nuclear collisions is studied with AMD in the above two reaction systems with equal mass and different isospin. Fragments are produced more abundantly in neutron rich $^{58}Fe + ^{58}Fe$ collisions than in $^{58}Ni + ^{58}Ni$ collisions in the energy region around 50 MeV/u, which is consistent to the data and may be related to the liquid-gas separation in two-component nuclear matter. In order to get the conclusion about the interesting effects in the flow in these reactions, more simulations should be performed to get better statistical accuracy.

(VIII) NON-EQUILIBRIUM PROCESSES AND OTHERS

a. Projection operator method for finite time evolution in ϕ^4 theory
(T. Koide, M. Maruyama and F. Takagi)

Shibata-Hashitsume's projection operator method was extended in order to calculate the time evolution of the field operators for initial states which are more general than those considered by Shibata et al. A new perturbative expansion formula was derived and is applied to ϕ^4 theory. It does not contain the time convolution integral. The resulting equation of motion indicates the validity of the linear harmonic approximation used in the influence functional method in order to eliminate the time convolution integral. Properties of the time-dependent divergence that occurs at the initial time was investigated in detail in connection with the renormalization of the usual ultraviolet divergence.

b. Time Evolution of Phase Transition at Finite Temperature in the Linear σ Model
(K. Sato and M. Maruyama)

We study time evolution of the chiral phase transition in the linear σ model. The equations of motion for the zero momentum modes of the σ and π meson fields are derived by using the projection operator method. The vacuum expectation value and the masses of the σ and π mesons are determined self-consistently. We also discuss about the consistecy of the result with the PCAC relation.

c. Adiabatic Mean-field Model for Dynamical Collective State Transitions of a Nuclear System
(T. Kohmura, Y. Hashimoto, H. Ohta and M. Maruyama)

We propose an adiabatic mean-field model for dynamical collective state transitions of a nuclear system. The transition process is described in terms of the nuclear mean-field wave functions which are adiabatically determined in the course of the transition. Solving the

eigenvalue equation for the Hamiltonian, we calculate the time evolution of the system. Applying the model to nuclear tunneling processes, we discuss the features of dynamical collective state transitions.

d. Projection Operator Method for Collective Tunneling
(T. Kohmura, M. Maruyama, H. Ohta and Y. Hashimoto)

We formulate a full order expression for nuclear collective tunneling in the projection operator method, using an appropriate model Hamiltonian. Collective tunneling transitions are characterized by the slight energy splitting of almost degenerate nuclear states under consideration. The energy splitting yields a time scale of the tunneling. We obtain the expressions, solving the projected Schrödinger and Liouville equations.

Publications

1) *Mass spectra and decay widths of hadrons in the relativistic string model*
M.Iwasaki and F.Takagi, Phys. Rev. D**59** (1999) 094024.

2) *Time development of vacuum structure in chiral phase transitions*
M.Ishihara and F.Takagi, Phys. Rev. C**59** (1999) 2221.

3) *Effects of friction on the chiral symmetry restoration in high energy heavy-ion collisions*
M.Ishihara and F.Takagi, Phys. Rev. C**61** (2000) 024903.

4) *Adiabatic Mean-field Model for Dynamical Collective State Transitions of a Nuclear System*
T.Kohmura, Y.Hashimoto, H.Ohta and M. Maruyama, Phys. Rev. C61 (2000) 034315

5) *Effects of β_6 deformation and low-lying vibrational bands on heavy-ion fusion reactions at sub-barrier energies*
Tamanna Rumin, Kouichi Hagino and Noboru Takigawa, Phys. Rev. C61(2000) 014605

6) *Study of clustering structure of ^{19}B by the use of fragmentation reaction*
H. Takemoto, H. Horiuchi and A. Ono, Prog. Theor. Phys. **101** (1999), 101

7) *Nucleon-induced fragment formation with antisymmetrized molecular dynamics*
Y. Tosaka, A. Ono and H. Horiuchi, Phys. Rev. C **60**, (1999), 064613

8) *AMD Study of Multifragmentation*
A. Ono and H. Horiuchi, *Proc. International Workshop XXVII on Gross Properties of Nuclei and Nuclear Excitations, Hirschegg, Kleinwalsertal, January 17–23, 1999.* (GSI, 1999) p. 273–282.

9) *Cluster Formation Dynamics in Medium Energy Nuclear Collisions*
A. Ono, *Proc. 7th International Conference on Clustering Aspects of Nuclear Structure and Dynamics, Rab, Croatia, June 14–19, 1999.* (World Scientific, 2000) p. 294–301.

Master Thesis (March 2000)

M1) *Screening Effect by Bound Electrons on Astrophysical Nuclear Reactions*
Sachie Kimura

M2) *Fermion Pair Creation and Time Evolution of Vacuum in Homogeneous Electric Field*
Yuji Nakazawa